



## Wind Tunnel Testing of Active Control System for Bridges

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**STRUCTURAL RELIABILITY THEORY**  
**PAPER NO. 159**

**IABSE 15th Congress, Copenhagen, June 16-20, 1996**

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# Wind Tunnel Testing of Active Control System for Bridges

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Palle Thoft-Christensen, born 1936, got his M.Sc. in civil engineering in 1960 and his Ph.D. in mathematical plasticity theory in 1963 from the Technical University of Denmark. His main research areas are structural reliability and optimization.

## Summary

This paper describes preparation of wind tunnel testing of the principle of using flaps to control the motion of suspension bridges. The experiments will take place at the Instituto Superior Tecnico in Lisbon, Portugal. The bridge section model is constructed of foam with an aluminium frame. The flaps are regulated by servo motors. Neural networks are used to position the flaps in the optimal positions.

## 1 Introduction

The purpose of the wind tunnel testing of active control of suspension bridges described in this paper is primarily to investigate the principle to use flaps to control the bridge excitation. Suggestions for implementation of active control surface systems are given by Ostenfeld & Larsen [4]. To investigate this principle a bridge section model equipped with flaps is constructed. In a real bridge approximately  $\frac{1}{3}$  of the central span will be equipped with flaps. The bridge section model is dimensioned to fit in a wind tunnel where the entrance to the test section is  $1.5 \text{ m} \times 1.5 \text{ m}$  and the maximum wind speed is  $40 \text{ m/s}$ . The bridge section model investigated is realistic compared to a real bridge, but no specific bridge is investigated.

The bridge section model is equipped with a flap in each side, each flap is able to rotate  $20^\circ$  in both directions. It is very important that the flaps can be regulated independently as the effect of two flaps instead of one is essential. The purpose of the flap in the leading edge is primarily to introduce a load on the bridge opposite to the motion of the bridge. The purpose of the flap in the trailing edge is primarily to change the direction of the wake. Flaps with different lengths compared to the width of the bridge section are investigated.

The wind tunnel is described in section 2. The bridge section model and the regulation system are described in section 3. The neural networks used to calculate the optimal positions of the flaps are described in section 4.

## 2 Wind Tunnel

The wind tunnel for building aerodynamics at the Instituto Superior Tecnico in Lisbon, Portugal is described in the ROLLAB Report RR 079 [1], see figure 1. The tunnel is of the open return type and has a test section size of  $1.5\text{ m} \times 1.5\text{ m} \times 5.0\text{ m}$  (nominal values). The maximum speed is  $40\text{ m/s}$ . The floor is horizontal so the side walls and the ceiling alone are compensated with regard to the boundary layer growth along the wetted surfaces of the test section.

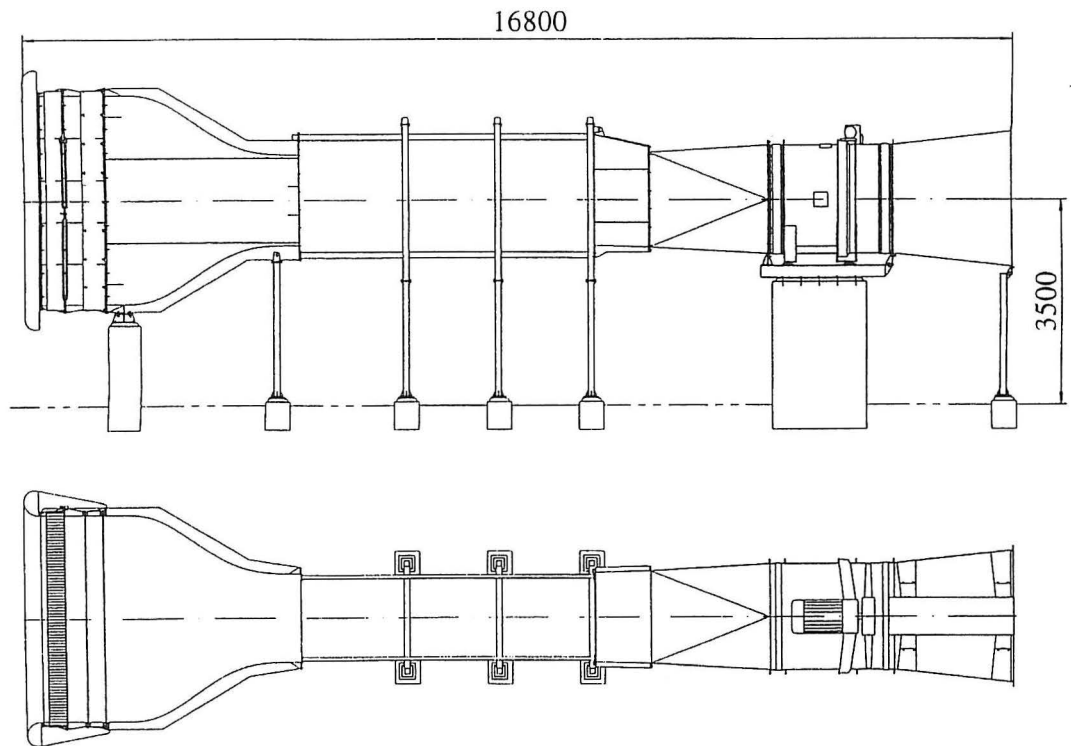


Figure 1: General layout of the wind tunnel. All lengths in mm, [1].

A collector (a funnel) will duct the air to a settling chamber where a honeycomb and two gauzes are installed. Thereafter a contraction unit (ratio 5.44:1) takes the air to the test section.

The nominal dimensions of the entrance to the test section is  $1.5\text{ m} \times 1.5\text{ m}$ . It is assumed that the boundary layer displacement thickness at this station is  $1.7\text{ mm}$ . This is in agreement with experienced values.

The test section steel “cage” will be mounted on separate steel frames bolted on concrete pads in the floor. Between the long top beams of the cage there are also short cross beams to make the test section rigid.

After the test section there is a diffuser/transition unit. At the end of the transition unit (from square to circular) a safety gauze has been installed so that the fan will be protected

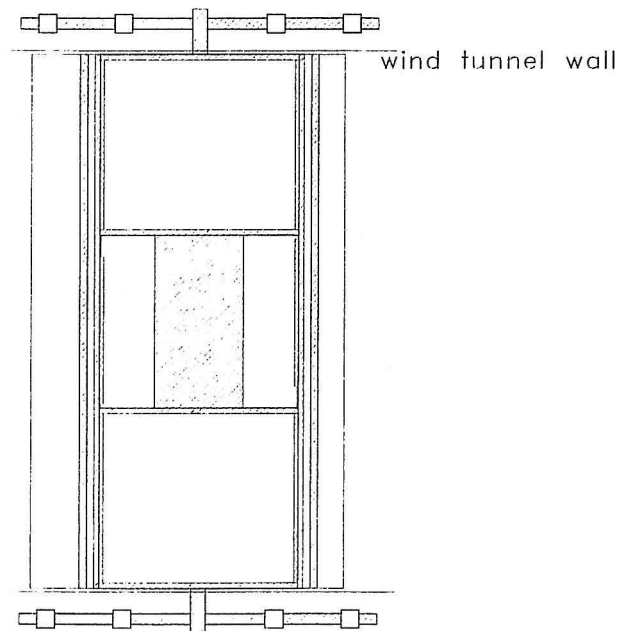
from loose elements or tools which may be forgotten in the test section.

In order to accommodate the ceiling to the top wall of the diffuser a special overbridging link must be introduced between the test section and the diffuser. After the fan a diffuser will terminate the wind tunnel leg.

Experimentally it has been demonstrated that fully turbulent flow could be assumed at a Reynolds Number  $\mathcal{R} = 10^6$ . In this case the calculated Reynolds Number  $\mathcal{R} = 1.32 \cdot 10^6$  (based on a speed of 40 m/s and a characteristic length of 0.5 m).

### 3 Description of Bridge Section Model

To get both a realistic weight of the model incl. flaps and regulation system depending on the model laws and a stiff model, the model is made of foam with an aluminium frame, see figure 2.



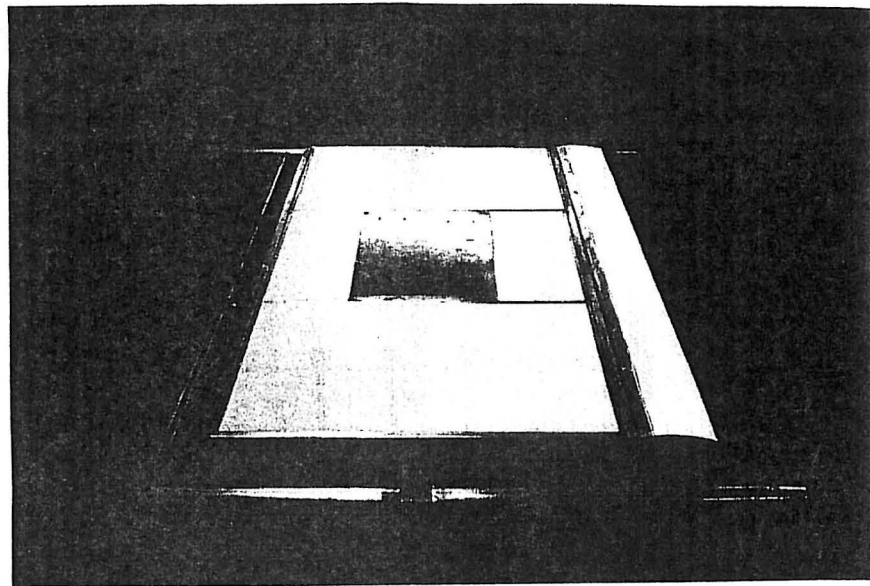
*Figure 2: Illustration of bridge section model seen from above, visible aluminium is hatched. A long flap is shown in the left hand side, and a short flap is shown in the right hand side.*

The bridge section model is suspended as described by Hjorth-Hansen [3]. The model is connected to a horizontal extension rod in each side which is going through the wind tunnel wall. The suspension system is the same in both sides. The extension rod is connected to an arm with dummy masses that can be moved on the arm so the model can represent the correct mass and mass inertia. Each side of the arm is suspended in two helical springs.



The spring constant for each suspension point is adjusted so as the two-dimensional model has the same eigenfrequency and damping ratio as the lowest symmetric bending eigenmode and the lowest torsion eigenmode of the real bridge, depending on the model laws. The damping of the model is ignored in the experiments. Additional damping can be made by letting a vane at each support plane shear through silicone oil as described by Hjorth-Hansen [3].

Each flap is positioned by a servo motor and reduction gear which are placed inside the bridge section model. The reduction gear is connected to the flap via a cable. The regulation system is dimensioned so the flaps are able to turn the possible  $40^\circ$  during  $\frac{1}{5}$  of the torsional eigen period of the model. The bridge section model equipped with short flaps is shown in figure 3.



*Figure 3: Bridge section model with short flaps.*

#### **4 Active Control of Bridge Section Model**

Active control of a structure requires that the new (discretized) state vector of the structure can be estimated based on the state vector, the load vector and the control force vector for the previous time step. Therefore, adaptive control algorithms must be used with simultaneous online structural system identification and vibration control. Unfortunately, there is no assurance of convergency for the extended Kalman filter even when it is used for linear problems. In the experiments the possibility of prediction of the state vector using neural networks is investigated. Further, the possibility for application of neural networks for estimation of optimal control forces is investigated.

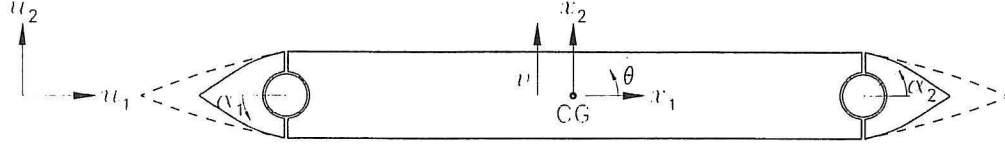


Figure 4: Definition of positive directions.

A  $(x_1, x_2)$ -coordinate system is defined in the centre of mass gravity CG of the bridge section, see figure 4. The  $x_2$  axis is defined to be positive upwards. The  $x_1$  axis is defined to be positive in the direction of the trailing edge (in the direction of the mean wind velocity).

The wind velocity  $\mathbf{u}(k)$  with the components  $u_1(k)$  and  $u_2(k)$  in the directions of the coordinate system is measured in the undisturbed stream in front of the leading edge at the discrete times  $t = k\Delta t$ ,  $k = 0, 1, \dots$

The positions of the flaps are given by the vector

$$\boldsymbol{\alpha}(k) = \begin{bmatrix} \alpha_1(k) \\ \alpha_2(k) \end{bmatrix} \quad (1)$$

where  $\alpha_1(k)$  and  $\alpha_2(k)$  are the angles of the flaps at the leading edge and the trailing edge, respectively. The angles are measured at time  $t = k\Delta t$  and are both positive in the positive rotation direction of the plane.

The bridge section is considered to be stiff and the motion in the direction of the  $x_1$  axis is ignored. Thereby, the bridge section has two degrees of freedom, selected as the vertical motion  $v(k)$  in the  $x_2$ -direction and the rotation in the positive rotation direction  $\theta(k)$  of the centre of mass gravity of the bridge section. The motion of the bridge section is then specified by the vector

$$\mathbf{x}(k) = \begin{bmatrix} v(k) \\ \theta(k) \end{bmatrix} \quad (2)$$

$\mathbf{x}(k)$  is measured at times  $t = k\Delta t$ ,  $k = 0, 1, \dots$

The following equation for the dynamic system is assumed

$$\begin{aligned} \mathbf{x}(k) &= \mathbf{f}(\mathbf{x}(k-1), \dots, \mathbf{x}(k-l), \mathbf{u}(k-1), \dots, \mathbf{u}(k-m), \\ &\quad \boldsymbol{\alpha}(k-1), \dots, \boldsymbol{\alpha}(k-n), \mathbf{w}_f) \end{aligned} \quad (3)$$

The control law is in the same way given by

$$\begin{aligned} \boldsymbol{\alpha}(k) &= \mathbf{g}(\mathbf{x}(k-1), \dots, \mathbf{x}(k-l), \mathbf{u}(k-1), \dots, \mathbf{u}(k-m), \\ &\quad \boldsymbol{\alpha}(k-1), \dots, \boldsymbol{\alpha}(k-n), \mathbf{w}_g) \end{aligned} \quad (4)$$

The functions  $\mathbf{f}$  (modelling the dynamic system) and  $\mathbf{g}$  (modelling the controller) are approximated by neural networks.  $\mathbf{w}_f$  and  $\mathbf{w}_g$  are vectors of weights and thresholds of the selected neural network topologies, [2]. The size of the tapped-delay lines defined by

$l$ ,  $m$  and  $n$  and the topology of the neural networks must be learned by experience from tests with the model.

The primary aim is the design of the controller  $\mathbf{g}$ , i.e. the specification of the control action (flap positions) at the time  $t = k\Delta t$  as a function of tapped delays of previous measured displacements, velocities and previous control actions. In principle control of the flaps could be determined from visual inspection of the displacements and velocities of the bridge via a joystick. Obviously, this is basically a closed-loop control of the bridge (the control action is only dependent on the present displacements and velocities). The digitalized control actions  $\alpha(k)$  along with the measured displacements  $\mathbf{x}(k)$  and velocities  $\mathbf{u}(k)$  could then be used to train the neural network (4) without any resort to the dynamic model (3). However there is a number of difficulties with such an approach. First, the method can hardly be carried out from a practical point of view because the fundamental eigenperiod of the model is as low  $T_m \approx 0.57$  s. Secondly, there is no guarantee, that any manual control is optimal in decreasing the vibrations. At least it seems likely that different people will select different control actions to the same displacement state, resulting in different vibration performance. Optimal control can only be specified if the vibration level is defined by a performance index. The dependency of such a performance index on the control action is evaluated by a dynamic model such as (3) with explicit dependency on previous control actions. Hence, optimal control relies on simultaneous modelling of the structural system and the control action.

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